NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

REPORT No. 525

SOME EFFECTS OF INJECTION ADVANCE ANGLE, ENGINE-JACKET TEMPERATURE, AND SPEED ON COMBUSTION IN A COMPRESSION-IGNITION ENGINE

By A. M. ROTHROCK and C. D. WALDRON

1935

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AERONAUTIC SYMBOLS

1. FUNDAMENTAL AND DERIVED UNITS

	Symbol	Metric		English	
		Unit	Abbreviation	Unit	Abbreviation
Length	l	meter	m	foot (or mile)	ft. (or mi.)
Time	t	second	s	second (or hour)	sec. (or hr.)
Force	F	weight of 1 kilogram	kg	weight of 1 pound	lb.
Power	P	horsepower (metric)		horsepower	hp.
Speed	V	kilometers per hour	k.p.h.	miles per hour	m.p.h.
		meters per second	m.p.s.	feet per second	f.p.s.

2. GENERAL SYMBOLS

W, Weight $= mg$

g, Standard acceleration of gravity $= 9.80665$ m/s^2 or 32.1740 ft./sec.^{2}

m, Mass $= \frac{W}{g}$

I, Moment of inertia $= mk^2$. (Indicate axis of radius of gyration k by proper subscript.)

μ, Coefficient of viscosity

ν, Kinematic viscosity

ρ, Density (mass per unit volume)

Standard density of dry air, 0.12497 kg-m^{-4}-s^2 at 15° C. and 760 mm; or 0.002378 lb.-ft.$^{-4}$ sec.^{2}

Specific weight of "standard" air, 1.2255 kg/m^3 or 0.07651 lb./cu.ft.

3. AERODYNAMIC SYMBOLS

S, Area

S_w, Area of wing

G, Gap

b, Span

c, Chord

$\frac{b^2}{S}$, Aspect ratio

V, True air speed

q, Dynamic pressure $= \frac{1}{2}\rho V^2$

L, Lift, absolute coefficient $C_L = \frac{L}{qS}$

D, Drag, absolute coefficient $C_D = \frac{D}{qS}$

D_o, Profile drag, absolute coefficient $C_{D_o} = \frac{D_o}{qS}$

D_i, Induced drag, absolute coefficient $C_{D_i} = \frac{D_i}{qS}$

D_p, Parasite drag, absolute coefficient $C_{D_p} = \frac{D_p}{qS}$

C, Cross-wind force, absolute coefficient $C_C = \frac{C}{qS}$

R, Resultant force

i_w, Angle of setting of wings (relative to thrust line)

i_t, Angle of stabilizer setting (relative to thrust line)

Q, Resultant moment

Ω, Resultant angular velocity

$\rho\frac{Vl}{\mu}$, Reynolds Number, where l is a linear dimension (e.g., for a model airfoil 3 in. chord, 100 m.p.h. normal pressure at 15° C., the corresponding number is 234,000; or for a model of 10 cm chord, 40 m.p.s. the corresponding number is 274,000)

C_p, Center-of-pressure coefficient (ratio of distance of *c.p.* from leading edge to chord length)

α, Angle of attack

ϵ, Angle of downwash

α_o, Angle of attack, infinite aspect ratio

α_i, Angle of attack, induced

α_a, Angle of attack, absolute (measured from zero-lift position)

γ, Flight-path angle

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Langley Memorial Aeronautical Laboratory

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SOME EFFECTS OF INJECTION ADVANCE ANGLE, ENGINE-JACKET TEMPERATURE, AND SPEED ON COMBUSTION IN A COMPRESSION-IGNITION ENGINE

By A. M. Rothrock and C. D. Waldron

SUMMARY

An optical indicator and a high-speed motion-picture camera capable of operating at the rate of 2,000 frames per second were used to record simultaneously the pressure development and the flame formation in the combustion chamber of the N. A. C. A. combustion apparatus. Tests were made at engine speeds of 570 and 1,500 r. p. m. The engine-jacket temperature was varied from 100° to 300° F. and the injection advance angle from 13° after top center to 120° before top center.

The results show that the course of the combustion is largely controlled by the temperature and pressure of the air in the chamber from the time the fuel is injected until the time at which combustion starts and by the ignition lag. The motion pictures of the combustion show that in a quiescent combustion chamber with a short ignition lag the flame first appears in the spray envelope and from there spreads throughout the chamber and that with a long ignition lag the flame may first appear in any part of the chamber. The conclusion is presented that in a compression-ignition engine with a quiescent combustion chamber the ignition lag should be the longest that can be used without excessive rates of pressure rise; any further shortening of the ignition lag decreases the effective combustion of the engine.

INTRODUCTION

When the N. A. C. A. combustion apparatus was first completed it was used to investigate the vaporization of the fuel spray under conditions of air pressure similar to those in a high-speed compression-ignition engine (references 1 and 2). The air temperatures throughout the cycle being considerably lower than those in an actual engine, the process could be studied without the influence of combustion. As a result of these tests it was found that the vaporization was much more rapid than had originally been believed. Although the tests did not in themselves show whether or not the combustion took place from the liquid or from the vapor phase, they did show that the vaporization was sufficiently fast that combustion could take place from the vapor phase; the conclusion was drawn that this was probably the case.

In the second series of tests (reference 3), in which fuel injection was used in conjunction with spark ignition, certain composite effects of air temperature, air pressure, and time on the combustion process were investigated. The tests showed that at low temperatures the rate of fuel combustion varied according to the volatility of the fuel but that at higher temperatures (and these higher temperatures were below those experienced in the conventional compression-ignition engine) both the rate and the extent of the combustion were apparently independent of the volatility of the fuel but were dependent on its chemical properties.

With these tests as a background, the investigations were extended to include compression ignitions under such conditions that the air temperature as well as the air pressure more nearly duplicated that experienced in the actual engine. In order to make such an investigation it was necessary to alter the N. A. C. A. combustion apparatus so that the air temperatures would be raised considerably and to use a high-speed motion-picture camera permitting the flame formation to be studied by means of individual photographs instead of in the one continuous photograph for the whole cycle, as in the previous tests. It is the purpose of this report to discuss tests with the altered apparatus that have been conducted on the effects of injection advance angle, engine-jacket temperature, and engine speed on the combustion process in a high-speed compression-ignition engine employing a quiescent combustion chamber. Preliminary reports on these tests have been presented in references 4 and 5.

The data were obtained at the Committee's laboratories at Langley Field, Va., during the latter part of 1933 and the early part of 1934.

APPARATUS AND METHODS

For the present tests a new injection system was added to the N. A. C. A. combustion apparatus and the original injection system was used to operate an automatic scavenging, or compression-release, valve (fig. 1). With the present arrangement the compression-release valve is controlled by valves C and D and the high-pressure reservoir. With this arrangement

full compression exists only for the single cycle in which the injection of the fuel occurs, the engine being scavenged on all preceding and succeeding cycles (fig. 2).

The apparatus is brought to speed by the electric driving motor. During this time, on each stroke of the piston the air is forced out through the compression-release valve in the cylinder head. On the down strokes the compression-release valve closes, because of the reversal of air flow, and a partial vacuum is created. When the piston uncovers the ports at the bottom of the stroke, fresh air is inducted into the displacement volume. The volumetric efficiency of the engine depends on the ability of the air to enter the ports during approximately 90 crankshaft degrees. Figure 3 shows the pressures in the combustion chamber during this scavenging process. The data were obtained with the N. A. C. A. gas-sampling valve (reference 6) used as a low-pressure indicator. At 570 r. p. m. the engine was approximately 87 percent scavenged on each stroke and at higher speeds up to 1,400 r. p. m. approximately 72 percent scavenged. An analysis of the gases in the cylinder during the scavenging process showed no indication of carbon dioxide.

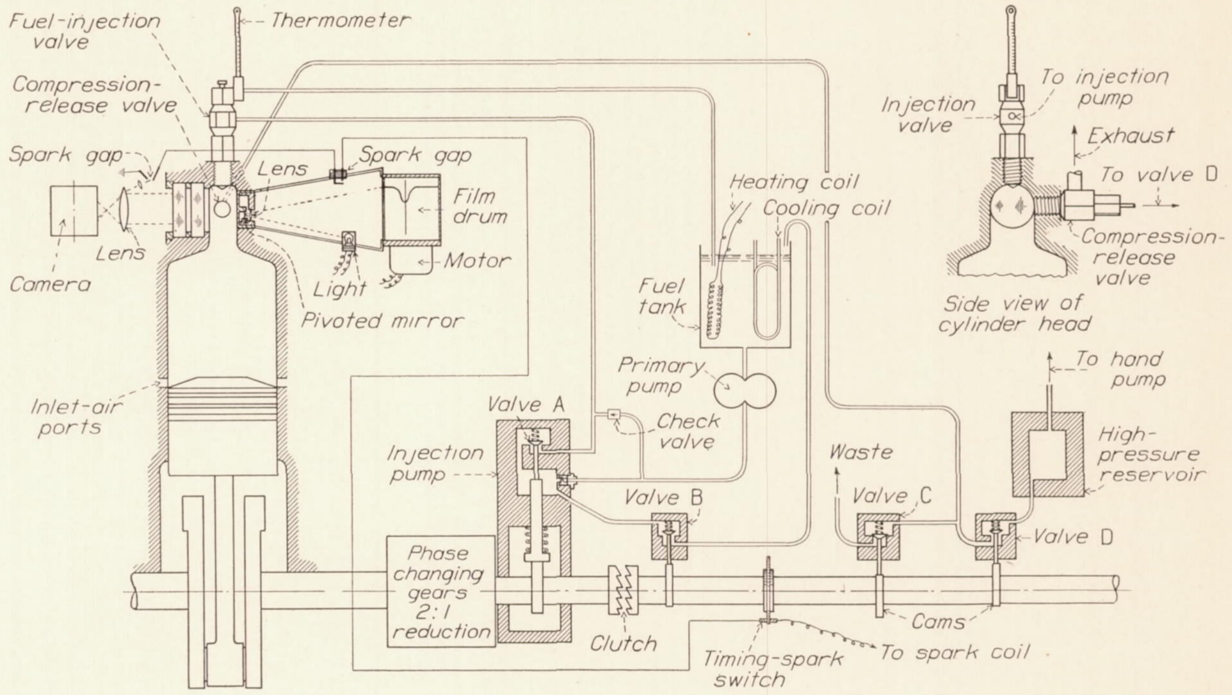

FIGURE 1.—Diagrammatic sketch of N. A C. A. combustion apparatus.

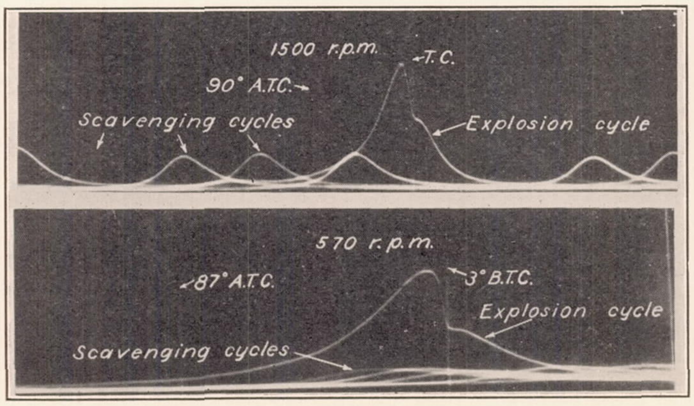

FIGURE 2.—Contact print of original indicator-card negatives. Injection start 10° before top center.

When the test speed is reached, the clutch is engaged for a single revolution of the camshaft, that is, for two revolutions of the crankshaft. When valve B closes, the plunger in the injection pump compresses the fuel in the small pump reservoir. This compression of the fuel holds the valve stem A against its seat so that none of the fuel can enter the injection tube from the small reservoir. Shortly before the pump plunger reaches the top of its stroke it engages the valve stem A, causing the stem to lift from its seat. A hydraulic pressure wave of high intensity is transmitted through the injection tube to the injection valve. Injection continues until the force exerted by the wave drops to a value less than the closing pressure of the injection valve. The fuel quantity discharged is controlled by the injection-valve opening pressure. The temperature of the fuel in the injection valve is maintained at a constant value by continuously circulating fuel from the fuel tank, through the injection tube, through four 0.010-inch holes to the center of the hollow injection valve stem, and back to the fuel tank.

The bore of the engine is 5 inches and the stroke, 7 inches. The height of the inlet ports is 0.5 inch. The

compression ratio, based on the 6.5-inch stroke, was 13.9 with the indicator and glass window installed and 13.2 with the windows in each side.

The six-orifice fuel-injection nozzle used is shown in figure 4. The spray photographs record no fuel being discharged from the two outside orifices, because the combined area of the orifices (equivalent to that of a single 0.060-inch orifice) was large in comparison with the passages through the injection valve (0.100 inch in diameter).

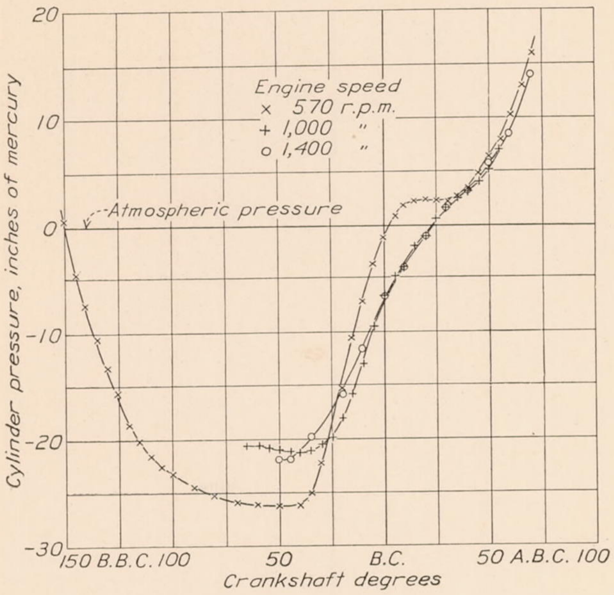

FIGURE 3.—Cylinder pressures during intake process.

Because the fuel used in the first part of the tests was unavoidably destroyed it was necessary to complete the tests with a second diesel fuel. Their distillation curves are shown in figure 5. Fuel 1 had a viscosity of 0.10 poise and fuel 2 a viscosity of 0.05 poise at 70° F. In all tests the fuel quantity was 0.00025 pound per injection, giving an estimated air factor of approximately 1.4. No differences were noted in the combustion characteristics of the two fuels.

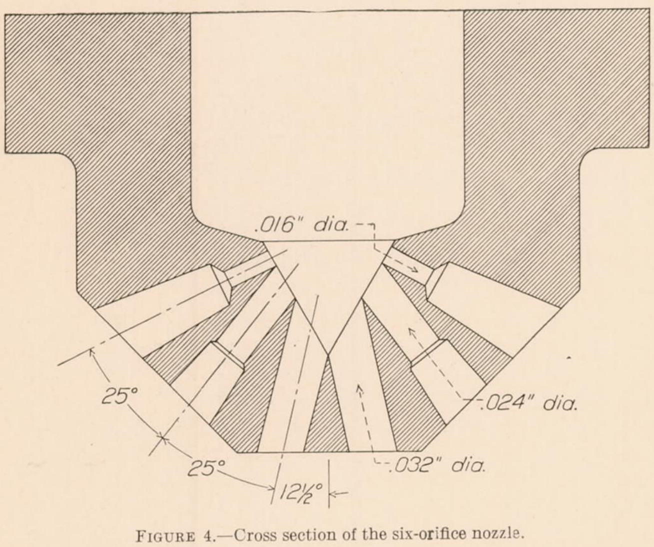

FIGURE 4.—Cross section of the six-orifice nozzle.

No apparatus is available at the laboratory for measuring the temperature of the compressed air during the operating cycle. The combustion characteristics of the tests reported herein have shown that a jacket temperature of 70° F. results in an air temperature in excess of that obtained with a jacket temperature of 350° F. before the present alterations were made to the apparatus. The present tests have also shown that with a cylinder and head jacket temperature of 100° F. the indicator cards are very similar to those in a normal high-speed compression-ignition engine, the operating range of injection advance angles being the same as that experienced in the various test engines in the laboratory. All temperatures given in this report are those of the glycerin as it left the jackets.

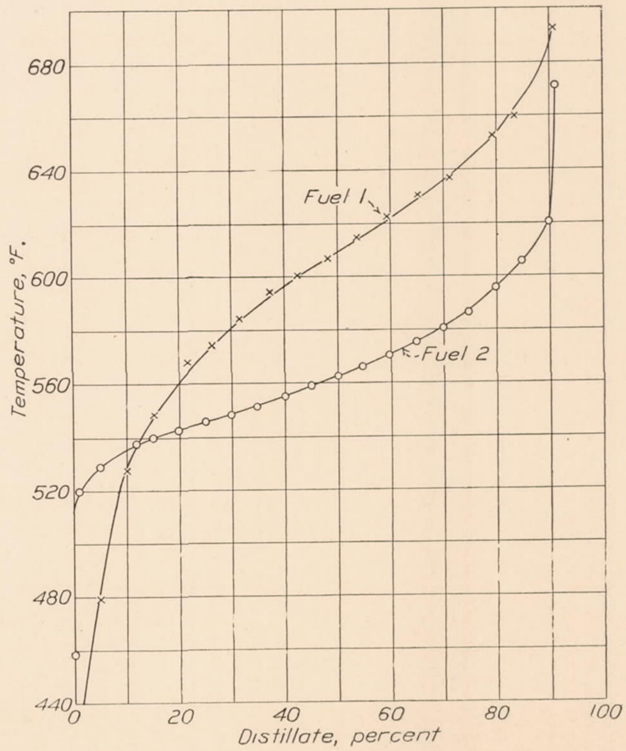

FIGURE 5.—Distillation curves (A. S. T. M. method) of the two fuels used in the tests.

In most of the tests herein reported a glass window was installed in one side of the combustion chamber and the optical indicator described in reference 3 in the other side. (See fig. 1.) A synchronous motor drove the indicator film drum at a constant peripheral speed of 100 inches per second. Because of the large stiff diaphragm in the indicator, the optical record closely followed the course of the pressure rise within the combustion chamber except in the case of detonation, which set the unit vibrating.

The camera used in these tests (reference 7) permitted high-speed motion pictures to be taken of the flame spread in the portion of the combustion chamber directly behind the 2½-inch glass window. This camera takes motion pictures at rates up to 2,250 frames per second by the use of a prism rotating at a high speed. The exposure time is one-third the time

interval between exposures. Although this time is considerably longer than that employed in the N. A. C. A. high-speed spark photographic system (reference 8), it is sufficiently short to study the flame formation in the combustion chamber. In order to synchronize the motion pictures of the flame spread with the indicator card, two sparks 90 crankshaft degrees apart were simultaneously recorded on the two records.

In another series of tests the indicator was removed and glass windows were installed in both sides of the combustion chamber. A 1,000-watt light was then directed through a ground glass onto the window that replaced the indicator. When the motion pictures were obtained with this set-up, a silhouette of the spray was recorded before the start of combustion. The intensity of the subsequent combustion was sufficiently greater than the intensity of the light from the bulb that the combustion was recorded on the film.

RESULTS AND DISCUSSION

INDICATOR CARDS

The most noticeable effect to be expected from a variation of injection advance angle and of engine-

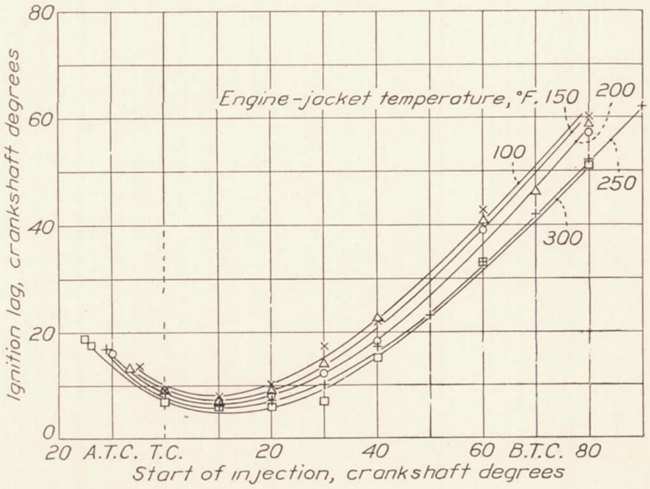

FIGURE 6.—Effect of injection advance angle on ignition lag at different jacket temperatures. Engine speed 570 r. p. m.

jacket temperature is on the ignition lag. In these tests the ignition lag is defined as the time interval between the start of injection as determined from injecting against a paper mounted on the engine flywheel and the start of pressure rise caused by combustion as shown on the indicator card. At 570 r. p. m. the results (fig. 6) show that the ignition lag decreases markedly as the injection advance angle is decreased, reaches a minimum, and then starts to increase. In each case the injection was retarded until ignition did not occur. The effect of increased jacket temperature was to decrease the ignition lag, considerably with long ignition lags, and to a lesser degree with short ignition lags.

The curves are of more interest if, instead of plotting the ignition lag as the ordinate, the start of combustion is plotted (fig. 7). The curves now show that as the start of injection is advanced the start

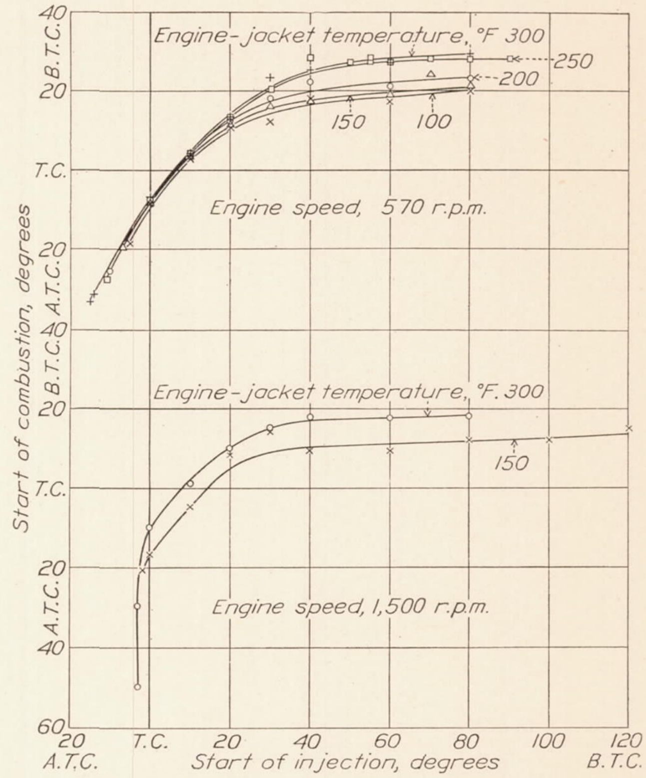

FIGURE 7.—Variation of start of combustion with injection advance angle and engine-jacket temperature.

of combustion tends to reach a limiting value and that this value increases as the engine-jacket tem-

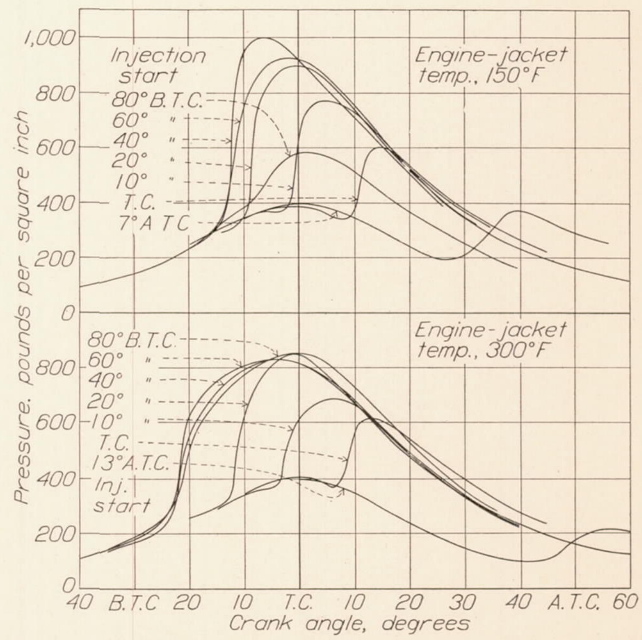

FIGURE 8.—Effect of injection advance angle on instantaneous cylinder pressures at an engine speed of 570 r. p. m.

perature is increased. This fact leads to the theory that in the compression-ignition engine there is a

minimum air temperature for each initial air pressure at which auto-ignition will occur and that, within the limits imposed by the apparatus, this temperature at a given engine speed is independent of the conditions to which the fuel has previously been subjected. The curves indicate that with the increased rate of pressure rise at the higher speed the limiting value of temperature is higher than was the case at the lower speed.

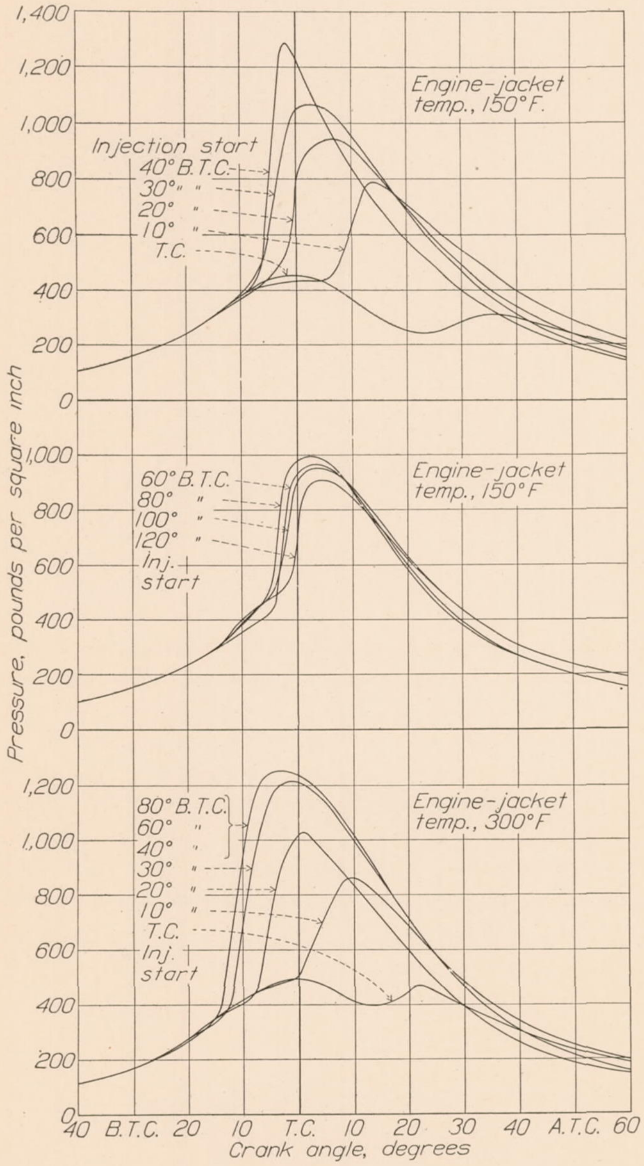

FIGURE 9.—Effect of injection advance angle on instantaneous cylinder pressures at an engine speed of 1,500 r. p. m.

That the rate and the extent of effective combustion are dependent on the air temperature and the pressure to which the fuel has been subjected before the start of combustion and on the time lag is indicated in figures 8 and 9. At an engine speed of 570 r. p. m. and an engine-jacket temperature of 150° F. (fig. 8), the rate of pressure rise increased as the start of injection advanced until, with an injection start of 40° before top center, the combustion took place with a decided knock. When the injection start was still further advanced to 80° before top center, the course of the combustion, but not the time of start, was changed decidedly. The burning was very weak and appeared to take place in two stages, an initial slow rate followed by an increase in the rate. This phenomenon was also found in the tests reported in reference 3. With the latest injection start the combustion took place slowly but, according to computations, to about the same extent as with the conventional advance angles. At an engine speed of 1,500 r. p. m. (fig. 9) and 150° F. jacket temperature the decrease in the rate of pressure rise with the earlier injection starts was not so marked.

When the engine-jacket temperature was increased to 300° F. at 570 r. p. m. (fig. 8), the first characteristic noticed was that the rate of pressure rise was decreased by the increase in the jacket temperature. This result was to be expected because of the decreased ignition lag. Other factors, however, are apparently effective because the rate of combustion, as indicated by the rate of pressure rise, was considerably less for the ignition lag of 55° with an injection advance angle of 80° before top center than for the lag of 24° with an injection advance angle of 40° before top center for the engine-jacket temperature of 150° F. The curves show that at the higher temperature the maximum rate of combustion occurs at an injection advance angle of about 60° instead of one of about 40°. At 300° F. the pressure curve at an injection start of 80° before top center very closely approaches that for a start of 40° before top center. Particularly noticeable at the higher jacket temperatures was the decrease in the rapidity of the burning as indicated by the sound of the explosion. At an engine speed of 1,500 r. p. m. and a jacket temperature of 300° F. (fig. 9) the rate of burning was less rapid than at the lower temperature and, up to an injection start of 80° before top center, no decrease in the maximum pressures or rates of combustion was evident. The curves indicate that the rate of burning based on degrees as well as on seconds was more rapid than at the lower engine speed.

An indication of the effectiveness of the combustion is shown in figure 10. It must be remembered that the explosion-pressure ratio P_1/P_2 is not an exact measure of the combustion efficiency because a certain amount of afterburning is not included when it takes place after the maximum pressure is reached and also because the pressure ratio depends to a certain extent on the initial temperature at the start of combustion. (See fig. 11.) In the present tests the P_1/P_2 ratio for complete combustion with no excess air is estimated from figure 11 to be between 4 and 6. When the injection was retarded at a jacket temperature of 150° F. and an engine speed of 570 r. p. m., the pressure ratio steadily increased to a maximum, decreased, and then sharply increased.

As the jacket temperature was increased, the first maximum occurred earlier in the cycle and decreased in magnitude until finally, at the highest temperature, the maximum disappeared altogether and the curve was approximately a straight line until the increase for injection start at top center occurred. The results indicate, as has already been shown to a considerably greater extent in reference 3, that as the ignition lag was increased the completeness of the effective portion of the combustion, except at high temperatures, first increased and then decreased. In those cases where detonation occurred it was with the injection advance angle that gave the first maximum value of the ratio. The cause of the sudden increase in the pressure ratio for the injection at or close to top center, but on the expansion stroke, cannot be explained.

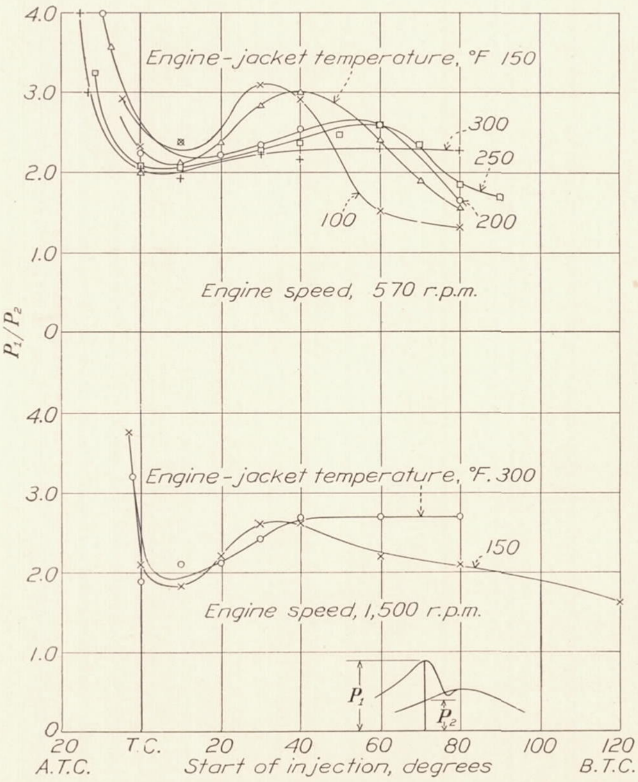

FIGURE 10.—Effect of injection advance angle on ratio of explosion pressure P_1 to normal compression or expansion pressure P_2.

At an engine speed of 1,500 r. p. m. the P_1/P_2 curves show the same effect to a lesser degree. At the higher speed the pressure ratio at 300° F. reaches the same maximum for the injection starts before top center as does the pressure ratio at 150° F. Comparison with the value for 570 r. p. m. shows that the ratio at 300° F. is slightly higher at 1,500 r. p. m. and that the maximum ratio for 150° F. is lower. The combustion at the higher speed was never accompanied by the severe knocking that occurred under the same conditions at 570 r. p. m. Again the sharp increase for combustion starting after top center is noticed. The curves again indicate a slightly greater effective combustion at the lower temperature for the operating range of injection advance angles, 20° to 40° before top center.

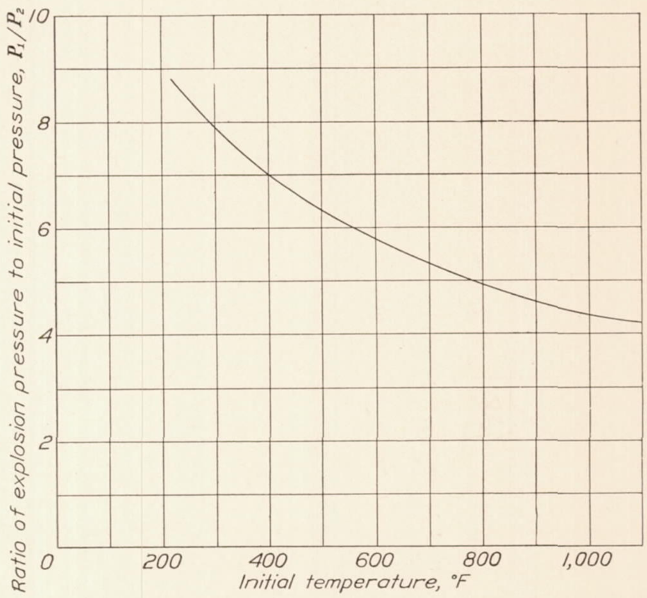

FIGURE 11.—Effect of initial temperature on computed ratio of explosion pressure P_1 to initial pressure P_2 with no excess air (variable specific heats).

Additional effects of the temperature on the course of the combustion at the lower engine speed are shown in figure 12. The rates of heat input to the gases in the combustion chamber were derived by the method discussed in reference 9. The curves show that when the jacket temperature was increased from 150° to 300° F. the ignition lag with an injection start of 10° before top center was decreased by about 2° and for an injection start of 20° before top center by about 3°. The course of the combustion as indicated by the rate-of-heat-input curves and by the pressure curves shows, however, considerable difference for the two temperatures at the later injection start, the same differences appearing to a lesser degree at the earlier

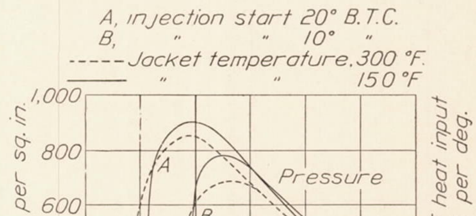

FIGURE 12.—Effect of jacket temperature on instantaneous cylinder pressures and rates of heat exchange. Engine speed 570 r. p. m.

injection. The maximum rate of burning, and consequently the maximum rate of pressure rise, was decreased by increasing the jacket temperature.

Increasing the jacket temperature in turn increased the air temperature throughout the compression stroke. Consequently, at the higher jacket temperatures the fuel was sprayed into hotter air. It had been hoped that this increased temperature would increase the rate of vapor diffusion of the fuel and so result in better mixing of the fuel and air. Although this result probably did occur, it was more than offset at the lower speed by the disadvantage of the decreased ignition lag and decreased air charge. When combustion started, any unmixed fuel had a more difficult time reaching the oxygen necessary for its combustion because the fuel already burned had diluted the oxygen with inert gases and had also decreased the oxygen content of the air. The data indicate that in a compression-ignition engine with a quiescent combustion chamber the ignition lag should be shortened only to that value which gives smooth running of the engine, for any further decrease of the ignition lag results in a poorer mixture of the fuel and the air at the time combustion is started and so results in a less effective combustion. This conclusion is supported by the results presented in reference 9 and has also been suggested by Boerlage and Van Dyck (reference 10). This statement implies that the ignition lag of many fuels now in use is sufficiently short and that the problem of the high-speed compression-ignition engine must be attacked to a greater extent from considerations of distribution at the time combustion starts, although the chemistry of the fuel must, of course, not be forgotten. At high engine speeds (1,500 r. p. m.) the differences in the indicated thermal efficiencies caused by increased jacket temperature are not marked and it is possible that an increased jacket temperature might be beneficial in such cases.

MOTION PICTURES OF FLAME FORMATION

The discussion thus far has been limited to the examination of the combustion phenomena as recorded by the indicator cards. The conclusions reached are given additional support from a study of the high-speed motion pictures of the flame formation and flame movement in that part of the combustion chamber behind the glass window. A description of these data will be given before their significance is discussed. When writing this description the motion pictures (reference 11) were projected and consequently the motion of the flame described in the subsequent pages is not always easily visualized from the figures as presented. For this reason the description is given in more detail than would otherwise have been the case. In addition to the reproductions of the whole of the period of inflammation, enlargements to 0.6 full size of the first four frames of the flame formation have been reproduced for the first series to permit a closer examination of this part of the combustion period.

In the entire series of photographs presented, the time scale has been obtained from an average of all the time scales of the films shown on any particular photo-

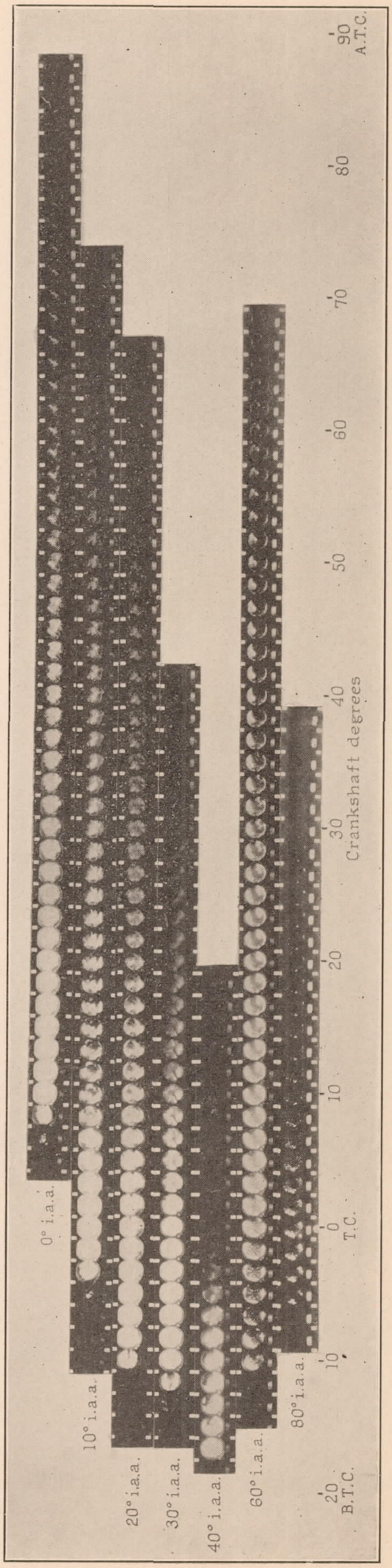

FIGURE 13.—Effect of injection advance angle on flame formation. Engine speed, 570 r. p. m.; engine-jacket temperature, 150° F.; fuel quantity, 0.00025 lb.

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graph. The speed at which the motion pictures were taken varied from 1,800 to 2,200 frames per second. The top center position may be one frame in error either to the right or left. The bottom of the combustion chamber is to the right in all the figures.

Reference to the first frame of figures 13 and 14 at an injection advance angle of 0° shows several areas of incandescence between the main sprays and between the main and auxiliary sprays, the light from the combustion illuminating part of the main sprays. In the second frame the flame has practically surrounded the sprays but has not as yet filled the chamber. In the third frame the flame fills most of the visible section of the chamber. During the whole of the flame spread there is no indication of orderly flame propagation, as is the case in the spark-ignition engine. This fact is to be expected when it is considered that, whereas with spark ignition there is only one source of flame start, with compression ignition there are innumerable sources. It must be remembered, however, that the indicator cards for the combustion period show more uniformity between successive cycles in the compression-ignition engine. During the whole of the period of luminescence there is an apparent indiscriminate motion of the flame. Whether this motion is flame travel or movement of the gases cannot be said except in the case of the period of afterburning when it is most probably gas movement. The afterburning is marked by well-defined regions of both luminous and nonluminous gases and there is a general downward movement of the flame because of the flow into the displacement volume.

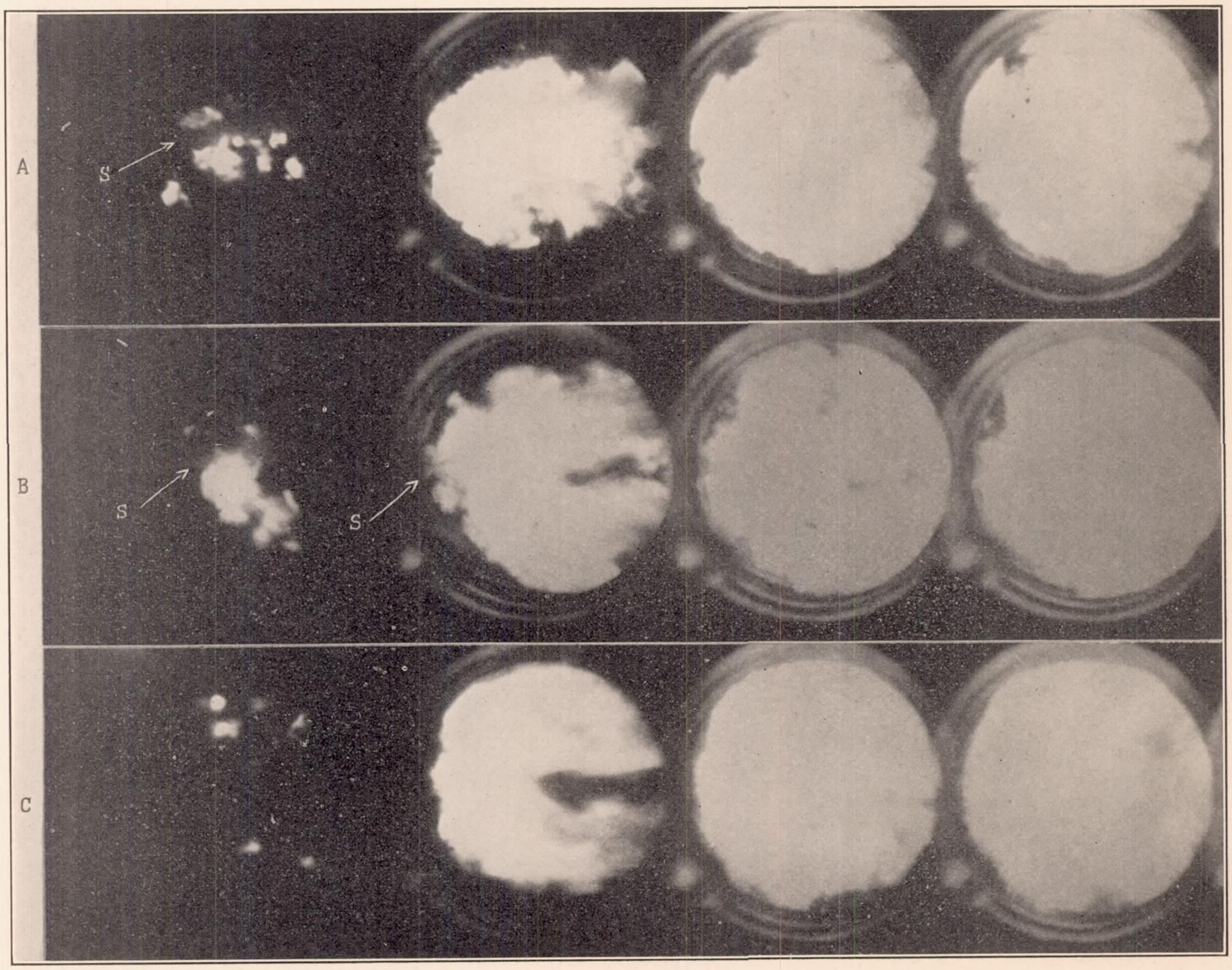

FIGURE 14.—Effect of injection advance angle on flame formation. Engine speed, 570 r. p. m.; engine-jacket temperature, 150° F.; fuel quantity, 0.00025 lb.; compression ratio, 13.9. A, i. a. a. 0°; B, i. a. a. 10°; C, i. a. a. 20°; S, fuel spray illuminated by flame. (See also fig. 13.)

For an injection start of 10° before top center, the first frame shows the flame starting around the spray cores and again the core of one of the main sprays is illuminated. In the second frame the flame has reached most of the visible portions of the chamber and the general outline of the sprays is still visible. In the third frame the flame has about reached its maximum spread. The flame movement is apparently more violent than with the later injection start. The motion pictures give an impression of churning through-

out the chamber but of no orderly movement of the gases as a whole. As before, with injection at top center there is a definite downward motion during the expansion stroke. The period of afterburning now shows the flame in more of the chamber without the flame has spread to most of the chamber except for an area between the lower portions of the two main sprays. This area is filled with flame in the next frame. After the fourth or fifth frame the flame seems to rotate counterclockwise at a high velocity. The rotation is

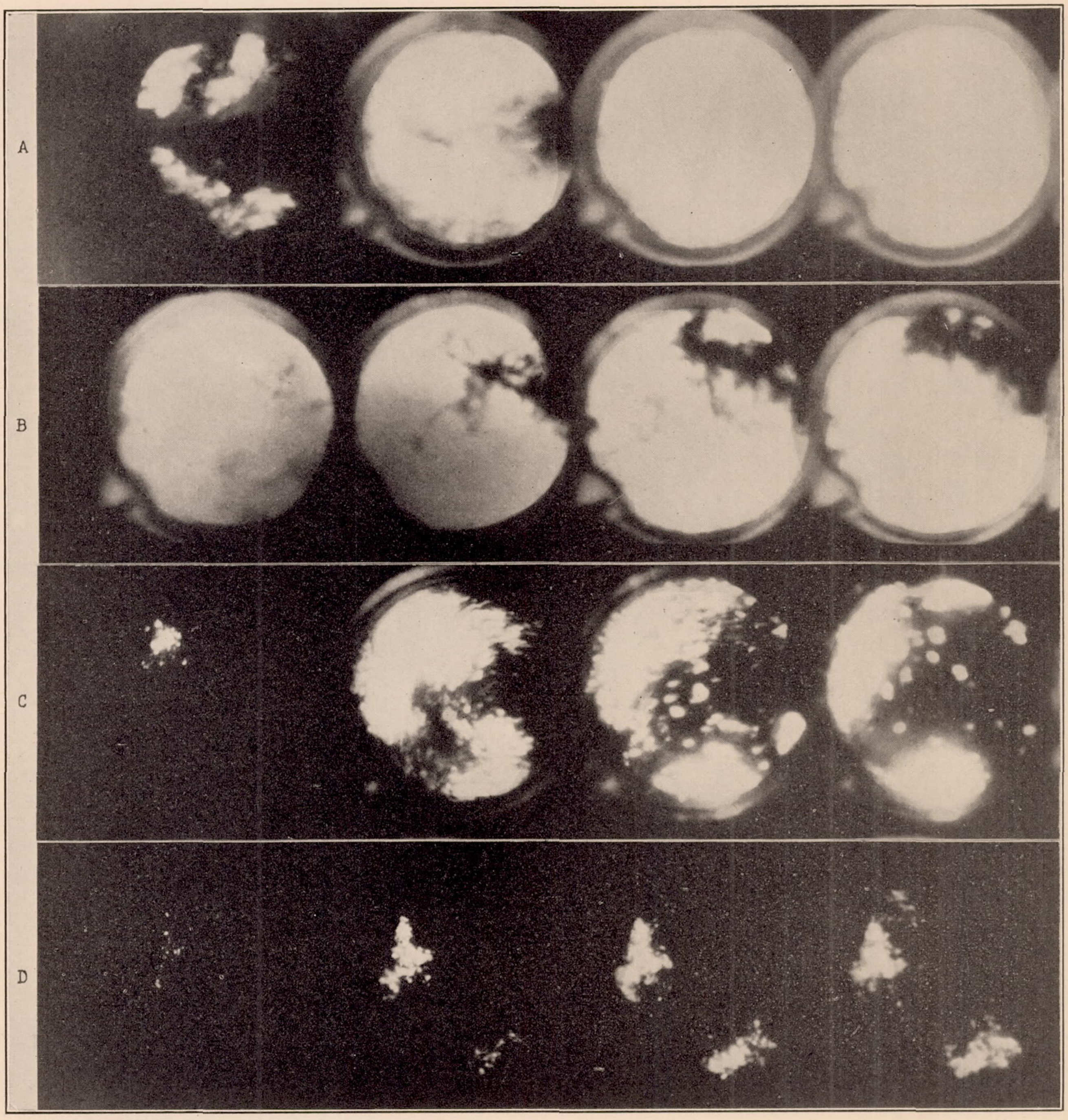

FIGURE 15.—Effect of injection advance angle on flame formation. Engine speed, 570 r. p. m.; engine-jacket temperature, 150° F.; fuel quantity, 0.00025 lb.; compression ratio, 13.9. A, i. a. a. 30°; B. i. a. a. 40°; C, i. a. a. 60°; D, i. a. a. 80°. (See also fig. 13.)

intensity of light; the areas of luminescence shade more gradually from light to dark.

When the injection start is 20° before top center, the first frame shows several spots of incandescence well distributed throughout the chamber but not defining the spray pattern. In the second frame the followed by the flame's again filling the chamber but with low intensity and a general downward movement accompanied by swirls within the flame. The shading from light to dark in the afterburning period is very gradual.

A comparison of the first frames of figures 13 and 15 where injection starts 30° before top center shows

the flame appearing at the edges of the chamber. In the second frame the flame has filled most of the chamber; the uniformity and the intensity of the flame increase in the next two frames. The flame is in general motion throughout the burning. The afterburning period is shorter than with the later injections and the flame disappears last in the center of the chamber.

When injection starts 40° before top center, the first frame shows the chamber brilliantly lighted throughout the visible portion. (This test run was characterized by severe knock.) Other tests under the same condition have shown the flame to start near the edge of the chamber. In the second frame the flame has started to disappear at the edge of the chamber, the dark spot growing larger in the successive frames, but the flame again spreads outward a few frames later. The afterburning period has disappeared and the flame last appears at the top of the chamber.

For an injection start of 60° before top center, the flame formation is very different from all those previously presented. The flame first appears to rotate counterclockwise but this rotation is suddenly stopped and the general flame pattern remains stationary except for the downward movement during the afterburning period. The flame is first recorded in the upper right-hand corner of the chamber and consists of numerous small "spheres" of light. The second frame shows areas of varying intensity throughout at least half the chamber. The blurring of the spots in this frame indicates the motion previously mentioned. The third frame shows the character of the flame to be changing and marks the end of the rotation. The upper left-hand section still shows the flame to be in motion but in the rest of the chamber it is stationary. In the successive frames the small areas of incandescence are seen to appear and disappear, some of them lasting for only one frame but producing a marked glow around the sections containing the greatest number of these small areas. The general appearance of the flame remains unaltered but the spots of light change position and the glow throughout the visible portion of the chamber increases in intensity. The period of afterburning is quite similar to that with the injection starting at top center. In repetitions of this test the general form of the flame was reproduced, although the parts of the chamber in which the flame predominated varied from one run to the next.

The first appearance of flame consists of several more or less isolated spots in the upper left-hand section for an injection start of 80° before top center. In the second frame, flame appears in both the upper left-hand and the lower right-hand sections. In every case the impression is given that the areas of flame consist of numerous individual spheres of incandescence existing for varying lengths of time. The flame never fills more than a small portion of the chamber and no general area of incandescence occurs, as it did with the injection start of 60° before top center.

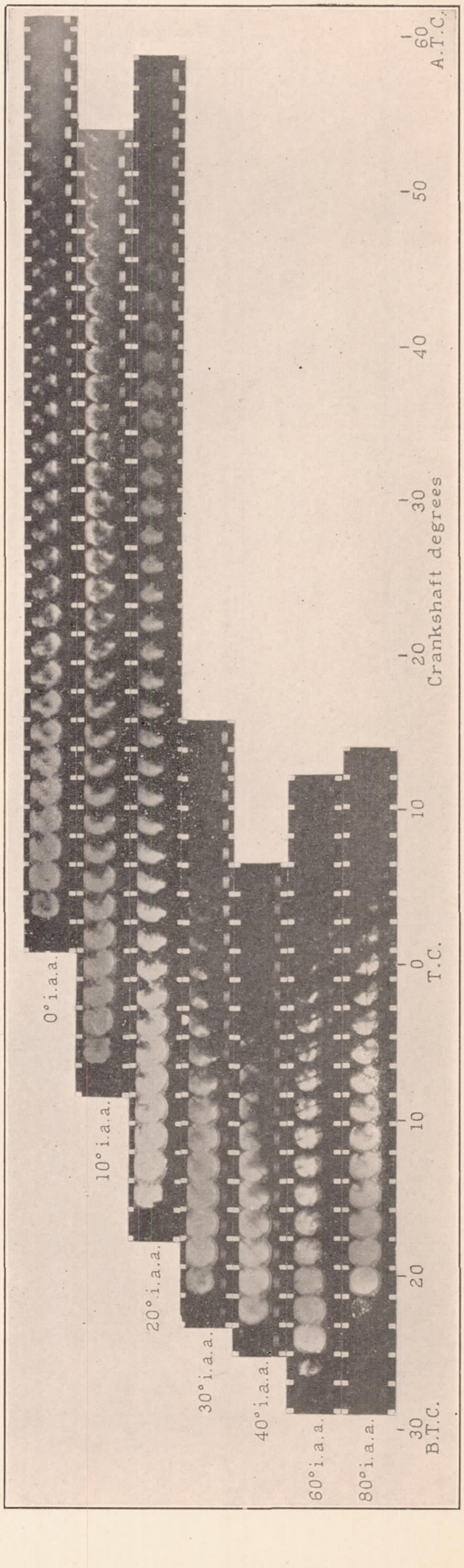

FIGURE 16.—Effect of injection advance angle on flame formation Engine speed, 570 r. p. m.; engine-jacket temperature, 300° F.; fuel quantity .0.00025 lb.

In general, the motion pictures of the flame at an engine speed of 570 r. p. m. and a jacket temperature of 300° F. (fig. 16) are similar to those taken at the lower temperature. With the exception of an injection advance angle of 40°, however, the flame period is shorter at the higher jacket temperature. The rate of spread of flame is greater during the initial burning period in spite of the fact that the higher temperatures made the burning smoother. The afterburning periods are, in no cases, characterized by the small bright areas of incandescence that appeared at the lower temperature with both the late and early injections. The results indicate that the vaporization and diffusion of the fuel were more rapid at the higher temperature.

The motion pictures of the flame taken at an engine speed of 1,500 r. p. m. and an engine-jacket temperature of 150° F. are shown in figure 17. The data show that at the higher engine speed the flame period in crankshaft degrees was considerably increased although the general formation of the flame remained unchanged. Even with the very early injection starts the flame filled all, or nearly all, of the visible portions of the chamber. With injection starts of 100° and 120° before top center the photograph of the flame was characterized by the same type of small brilliant areas that were photographed at the lower speed. It is interesting to note that with the injection starting at top center the start of flame was late enough on the expansion cycle so that the downward movement of the gases prevented the flame's reaching the top of the combustion chamber except at the core of the fuel sprays close to the nozzle.

MOTION PICTURES OF FUEL SPRAYS AND OF FLAME

The results obtained when the glass windows were placed in both sides of the combustion chamber with a 1,000-watt lamp focused on the side opposite the high-speed motion-picture camera are shown in figures 18 and 19. In figure 18, which represents the same conditions as figure 14A except for the slightly lower compression ratio, the two main sprays are seen to extend across the visible portion of the chamber. No fuel issued from the two outside orifices of the six-orifice nozzle. The sprays from the two 0.024-inch orifices did not reach the chamber walls. The sprays are all clearly visible in the fourth frame in which the start of the flame is shown in the envelope of one of the main sprays. Other photographs taken under the same conditions have shown the flame to start in the envelope of one of the outside sprays (reference 5). In all the tests made under these conditions the flame has first appeared near the core, that is, in the envelope, of one of the sprays. In the fifth frame the flame has spread around the upper main spray and has started around the second main spray, but both sprays are still visible. In the sixth frame the flame has spread still farther, but one of the main sprays can still be seen. In the seventh frame the sprays are no longer visible, being either completely obscured by the flame or sufficiently vaporized so that they do not show. The photographs clearly show how with a short ignition lag the fuel still in the liquid phase is surrounded by the burning mixture and that the unburned fuel must get through this burning portion to mix with fresh air.

In figure 19, comparable with figure 15B, the spray is seen to issue from the four center orifices; the two outside sprays reach the edge of the combustion chamber. The effects of the lower air density on the increased penetration and decreased rate of spray diffusion are noticed. The fuel apparently continues to issue from the two center or main orifices after discharge has stopped from the two 0.024-inch orifices. Cut-off occurs at about 30° before top center and the sprays then begin to lose their definite form. The process of the spray diffusion and vaporization is visible in the eighth to twelfth frames. From 20° to 14° before top center, no fuel is visible. Vaporization is now apparently quite complete. At 14° before top center the flame first appears and by the next frame the flame has spread to most of the chamber. In this case, with the increased time interval for the mixing of the fuel and air, the mixture that has been formed by the time the combustion starts is such that the flame spreads throughout the chamber with extreme rapidity and the burning is extremely rapid.

In a discussion of the flame photographs as a whole the question may be asked: Does the combustion itself produce turbulence in the burning gases? The projection of the motion pictures shows various types of movement within the flame. These movements have been discussed in the descriptions of the photographs and may be divided into two classes—those in which the flame moves as a single unit and those in which there is an apparent churning within the flame. Any apparent movement of flame may be caused by either of two actions. The gases may be stationary and the flame spreading through these gases, or the gases may be incandescent and actually in motion. Probably both of these phenomena occur to a certain extent. The burning raises the temperature of the gases in that portion of the chamber in which it is taking place and, as a result, raises their pressure. The increase in pressure causes an expansion of the gases and therefore a movement of the gases in front of the flame. In this case the rate of movement would be controlled by the force exerted by the increased pressure and by the inertia of the gases to be set in motion. Unless there is a visible body the movement of which can be observed, any conclusion as to the type of movement taking place must be a matter of conjecture. In certain of the films there are isolated spots of flame during the afterburning that do not appear to move with the rapidity of the flame as a whole. This

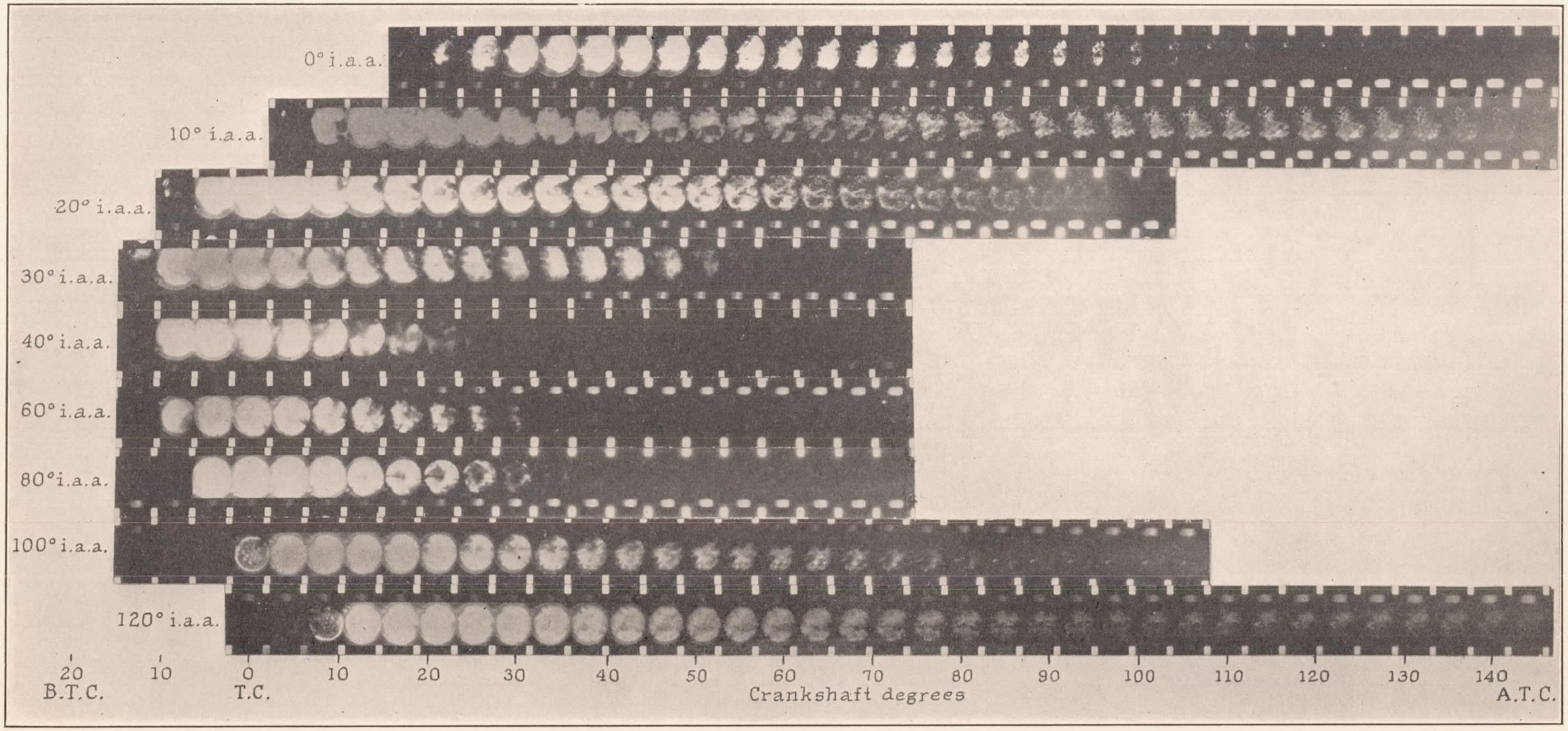

FIGURE 17.—Effect of injection advance angle on flame formation. Engine speed, 1,500 r. p. m.; engine-jacket temperature, 150° F.; fuel quantity, 0.00025 lb.

phenomenon would indicate that the motion of the flame is not that of moving gases. The point must not be lost sight of, however, that these spots of incandescence may be solid carbon, in which case their own inertia would cause them to move at a slow rate. Of course, the general downward movement of the flame in the afterburning period is certainly a mass movement of the gases caused by their expansion into the displacement volume. It is probable that the apparent eddies in the flame are also gas movements. It is the opinion of the authors that in the period of initial burning the apparent movement is that of the flame and not the gases except as the gases are compressed ahead of the flame; particularly does this statement apply to the violent rotations that occur with the rapid rates of burning. (See also reference 12.)

may not be of importance. It is quite possible that some of the gases were incandescent but they were not at the time in the visible portion of the chamber; this condition does not seem likely from the general appearance of the start of flame as registered on the photographic film. The appearance of flame is an indication of the energy state of the molecules of the gas and not necessarily of any chemical reactions that may be taking place in the gas. In other words, any chemical reaction may or may not be completed during the time the flame is still filling the chamber. Examination of the cases under consideration shows that the pressure of combustion first increased slowly during the nonluminous period followed by a more rapid increase during the luminous period. All the gases will need to be photographed during the whole period between

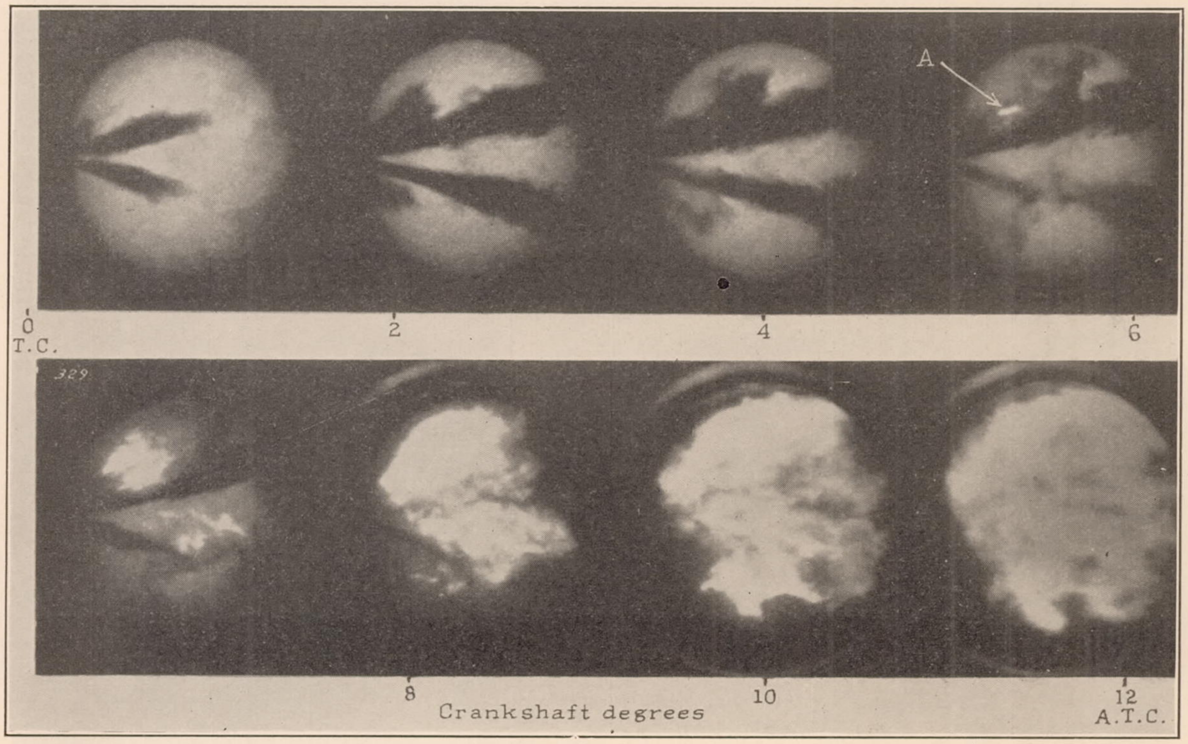

FIGURE 18.—High-speed motion pictures showing the fuel spray and the flame formation under nondetonating conditions. Engine speed, 570 r. p. m.; engine-jacket temperature, 150° F.; fuel quantity, 0.00025 lb.; compression ratio, 13.2; i. a. a. 0°. A, flame start.

Comparison of the flame photographs with the indicator cards taken either simultaneously or under similar conditions shows that the maximum rate of pressure rise occurs with the maximum rate of flame spread and not with the maximum amount of flame. Whether or not this latter period is the final formation of water and carbon dioxide as has been suggested by Marvin, Caldwell, and Steele (reference 13) for the spark-ignition engine, cannot be said.

A comparison of the indicator cards at the early injection starts, notably 80° injection advance angle at 570 r. p. m. and 150° F. jacket temperature, shows that there was heat input to the system because of combustion before flame was photographed in the visible portion of the combustion chamber. This fact may or

injection and the end of combustion before definite conclusions can be drawn as to whether or not the initial period of burning is accompanied by luminosity.

The tests presented in the present report and in reference 3 indicate that the general problem of combustion in the compression-ignition engine and in the spark-ignition engine have much in common and that data directly applicable to the compression-ignition engine can be obtained by the use of spark ignition. Consequently, it is possible to conduct tests in a constant-volume bomb with spark ignition and so separate some of the combined effects of temperature, pressure or density, and time. Such tests are being conducted at this laboratory and may lead to some explanation of the various effects already presented.

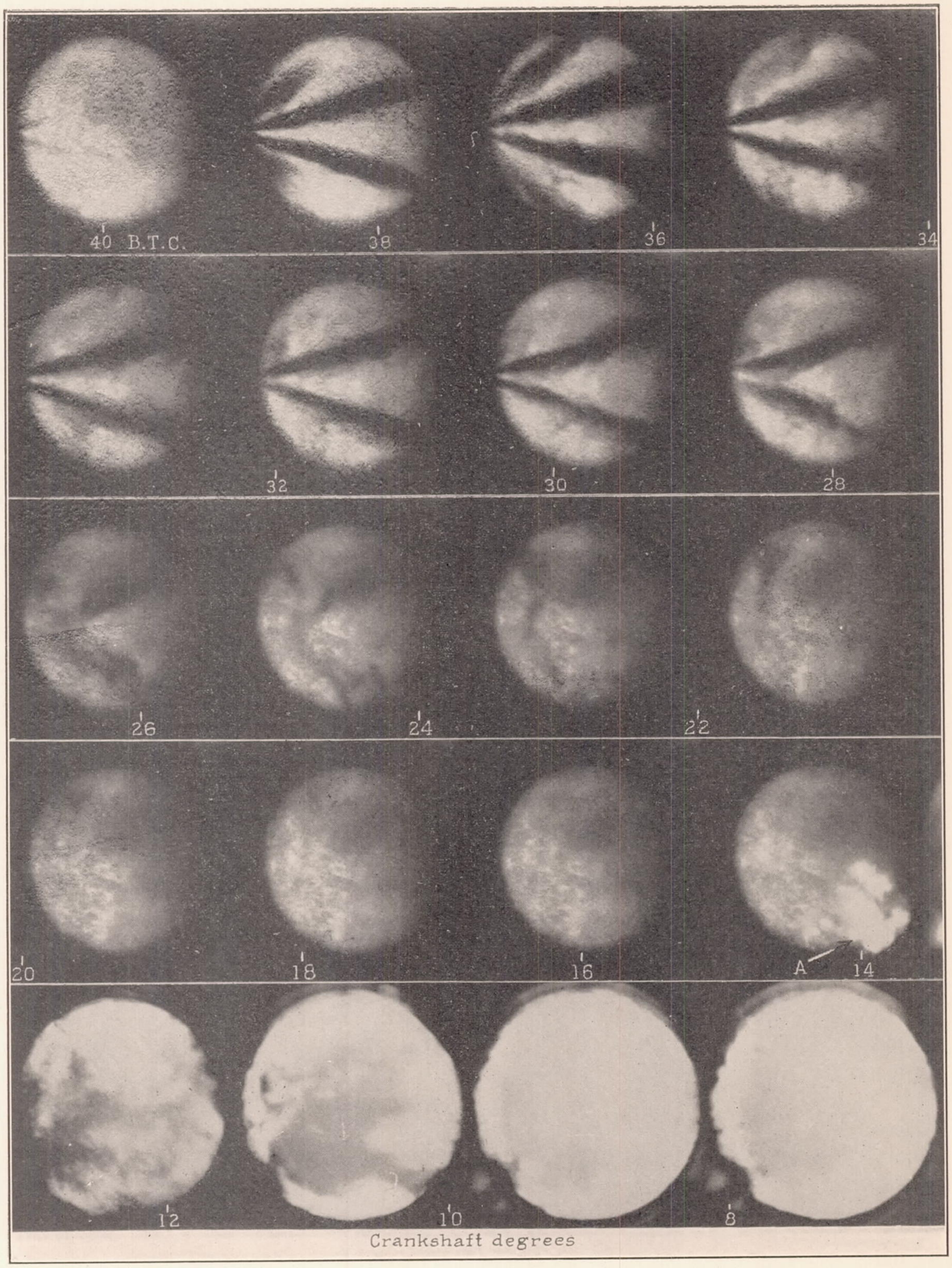

FIGURE 19.—High-speed motion pictures showing the fuel spray and the flame formation under detonating conditions. Engine speed, 570 r. p. m.; engine-jacket temperature, 150° F.; fuel quantity, 0.00025 lb.; compression ratio, 13.2; i. a. a. 40°. A, flame start.

CONCLUSIONS

The following conclusions are presented:

1. The ignition lag in an engine with a quiescent combustion chamber should be decreased to that value required to prevent objectionable rates of pressure rise. The ignition lag should not be decreased to less than this value because by so doing the effectiveness of the combustion is decreased.

2. With a short ignition lag in a quiescent combustion chamber the burning starts in the spray envelope and from there spreads throughout the combustion chamber. With a long ignition lag the burning may start at any point in the chamber. In either case the burning may start at one point or simultaneously at several points.

3. The course of the combustion (aside from the original chemical properties of the fuel) is affected by:

a. The time interval between the start of injection and the start of combustion.

b. The temperatures and pressures existing in the combustion chamber during this time interval.

c. The temperature and pressure of the air and the distribution of the fuel at the start of combustion.

4. In case the ignition lag is too long it may be decreased considerably by increasing the temperature of the engine coolant.

5. If the ignition lag is short, increasing the temperature of the engine coolant decreases the ignition lag sufficiently to decrease the rate of pressure rise but may in some cases decrease the effective combustion of the engine.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., *January 15, 1935.*

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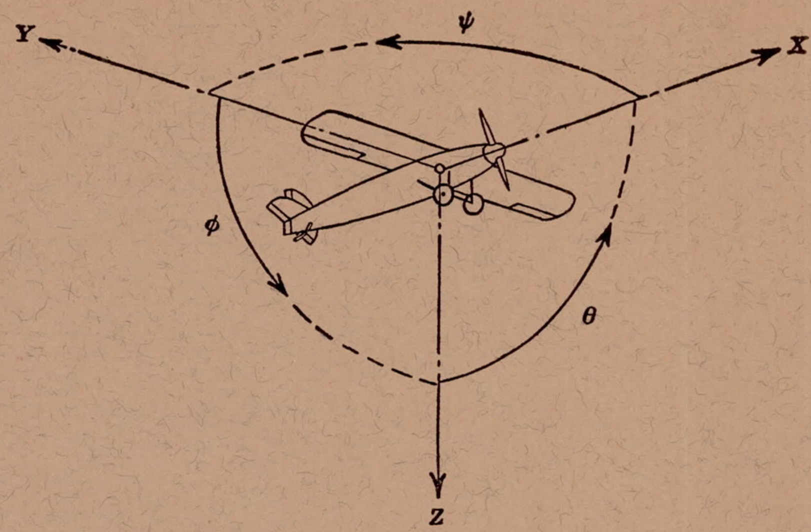

Positive directions of axes and angles (forces and moments) are shown by arrows

Axis		Force (parallel to axis) symbol	Moment about axis			Angle		Velocities	
Designation	Symbol		Designation	Symbol	Positive direction	Designation	Symbol	Linear (component along axis)	Angular
Longitudinal	X	X	Rolling	L	$Y \longrightarrow Z$	Roll	ϕ	u	p
Lateral	Y	Y	Pitching	M	$Z \longrightarrow X$	Pitch	θ	v	q
Normal	Z	Z	Yawing	N	$X \longrightarrow Y$	Yaw	ψ	w	r

Absolute coefficients of moment

$C_l = \frac{L}{qbS}$ (rolling) $\quad C_m = \frac{M}{qcS}$ (pitching) $\quad C_n = \frac{N}{qbS}$ (yawing)

Angle of set of control surface (relative to neutral position), δ. (Indicate surface by proper subscript.)

4. PROPELLER SYMBOLS

D, Diameter
p, Geometric pitch
p/D, Pitch ratio
V', Inflow velocity
V_s, Slipstream velocity
T, Thrust, absolute coefficient $C_T = \frac{T}{\rho n^2 D^4}$
Q, Torque, absolute coefficient $C_Q = \frac{Q}{\rho n^2 D^5}$
P, Power, absolute coefficient $C_P = \frac{P}{\rho n^3 D^5}$
C_s, Speed-power coefficient $= \sqrt[5]{\frac{\rho V^5}{P n^2}}$
η, Efficiency
n, Revolutions per second, r.p.s.
Φ, Effective helix angle $= \tan^{-1}\left(\frac{V}{2\pi r n}\right)$

5. NUMERICAL RELATIONS

1 hp. = 76.04 kg-m/s = 550 ft-lb./sec.
1 metric horsepower = 1.0132 hp.
1 m.p.h. = 0.4470 m.p.s.
1 m.p.s. = 2.2369 m.p.h.
1 lb. = 0.4536 kg.
1 kg = 2.2046 lb.
1 mi. = 1,609.35 m = 5,280 ft.
1 m = 3.2808 ft.